Brazing Dissimilar Metals with a Novel Composite Foil

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JOHNS HOPKINS
WHITING SCHOOL of ENGINEERING

Project ID
LM098

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Overview

Timeline

- Start date: October 1, 2013
- End date: December 31, 2017
- Percent complete: 75%

Barrier

- Joining and assembly. High-volume, high-yield joining technologies for lightweight and dissimilar materials need further improvement.

Budget

- Project budget: $595,520
  - Budget Period 3: $152,885

Project Partners

- Dr. Karsten Woll – Karlsruhe Institute of Technology, Karlsruhe, Germany
- Dr. James K. Guest and Dr. Reza Behrou – Johns Hopkins University
- 3M

Relevance – Project Objectives

DOE Objective: Enable new multi-material joining techniques to introduce more light weight components for auto assembly.

Project Objective: Develop and characterize novel reactive foils based on reduction-oxidation (Redox) reactions for use in bonding dissimilar materials.

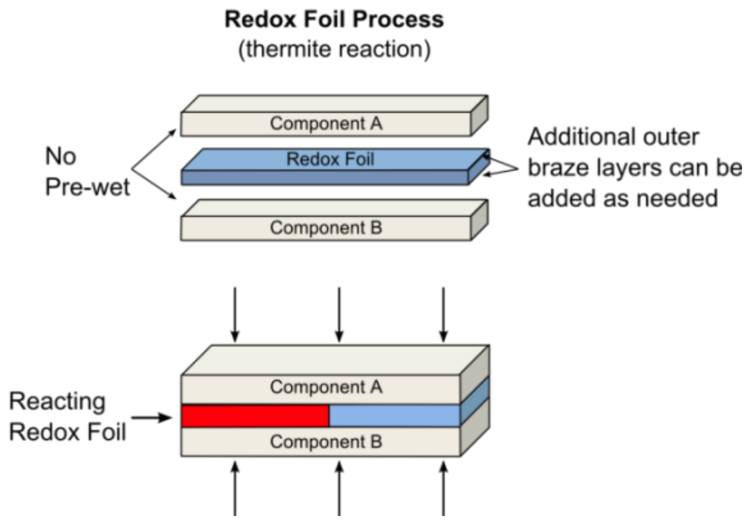
Achievements for FY2016:

- Identified Cu vapor as the gaseous species during propagation of reactions with a Al:Cu_2O:Cu chemistry.
- Produced vapor-deposited Al:Cu_2O:Cu foils with five different diluent amounts to identify an idealized microstructure, with impact verified by modeling.
- Increased homogenization of the diluent in Redox Foils by incorporating the diluent into the ball-milling process.
- Reduced the solidification temperature on cooling by over 100°C by replacing the Cu diluent with Ag.

Milestones

Task	2014				2015				2016				2017				Milestones	Status
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4		
1. Optimize Foil Properties																		
1.1 Optimize chemistry							M1										Dissimilar Bonds with strength 10MPa	Complete
1.2 Optimize microstructure							M2										Microstructures with no gas production and quenching	Complete
1.3 Optimize mechanical fab									M3								Optimized methods for mechanically fabricating Redox Foils	Complete
2. Optimize Bonding Parameters																		
2.1 Applied pressure											M4						Optimize applied pressure	Complete
2.2 Foil thicknesses											M5						Optimize foil thickness	Complete
2.3 Surface preparation												M6					Optimize surface preparation.	Complete
3. Characterize Bond Properties – Microstructure																		
3.1 Bond strengths																M7	Statistical bond strength data	ISSUES
3.2 Failure modes																M7	Determine failure modes of bonds	On Track
3.3 Corrosion behavior															M8		Determine galvanic corrosion behavior of optimized bonds	ISSUES
3.4 Bond/component microstructure																M9	Analyze microstructure at bond interface	On Track
3.5 Component degradation																M9	Analyze degradation of bonds	ISSUES

Approach – Exothermic Brazing



$$2Al + 3Cu_2O + xCu \rightarrow Al_2O_3 + (6+x)Cu + Heat$$

- Redox Foils: nearly fully dense diluted thermites
  - Produce braze and heat
- Dilute with excess metal to decrease amount of gas produced
  - Want reaction temperature below boiling points (no gas production)

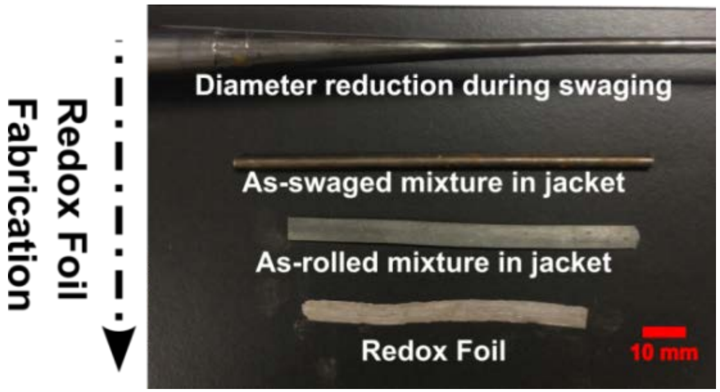
Fuel Oxide

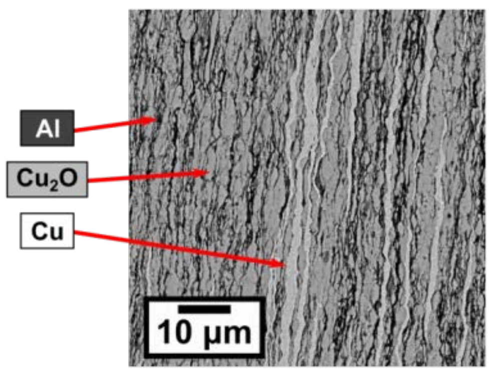
$Al:Cu_2O:20\%Cu$

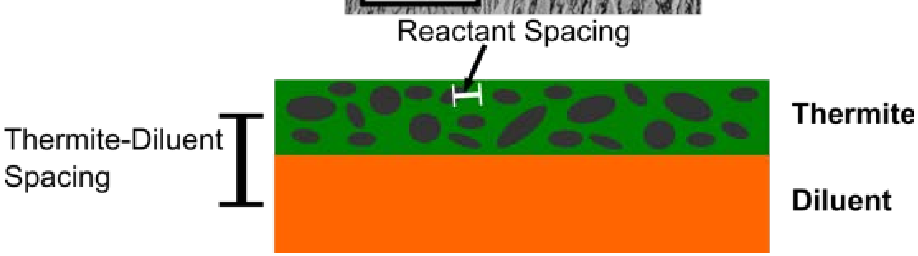
Diluent

Approach – Fabrication Methods

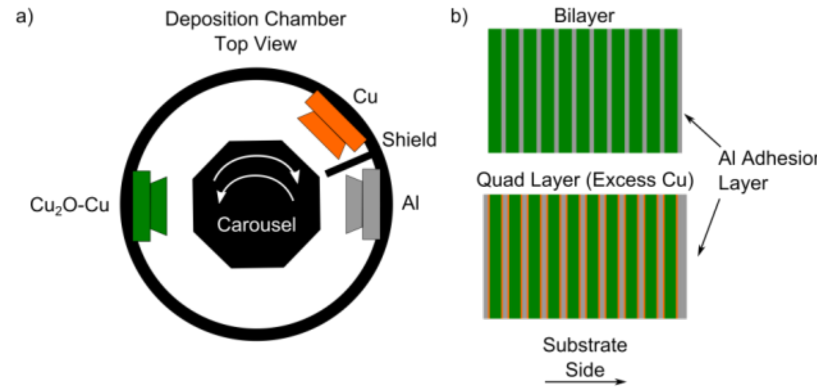
Powder Processing

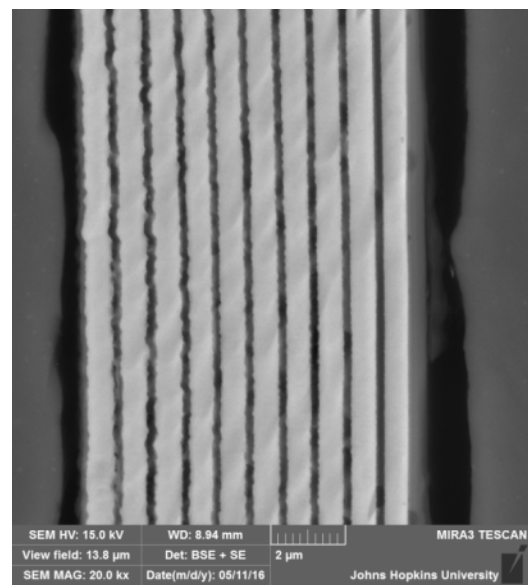






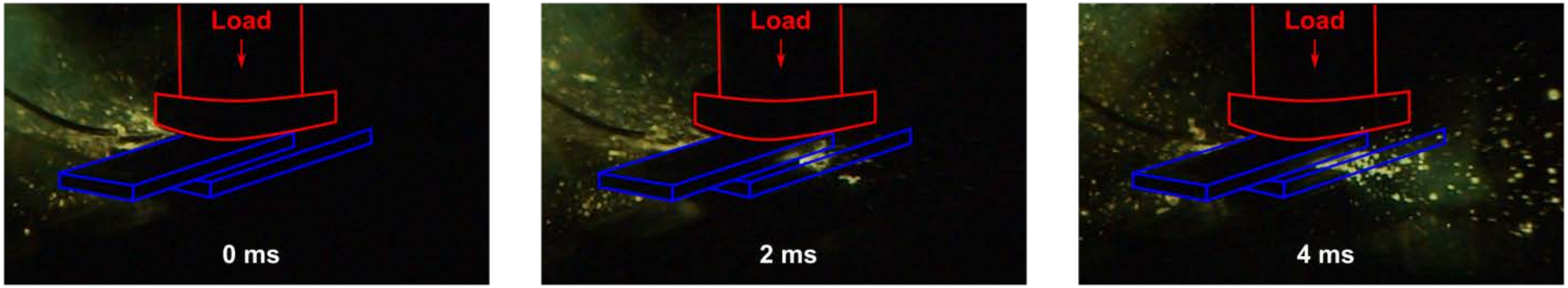
Vapor Phase Processing (PVD)

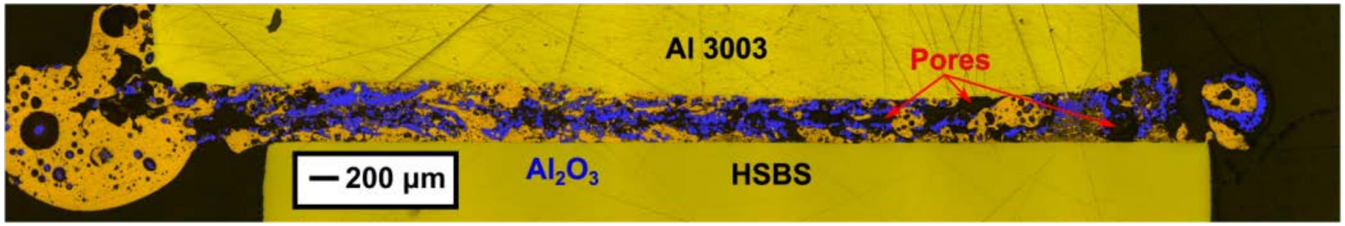




Controlled microstructure

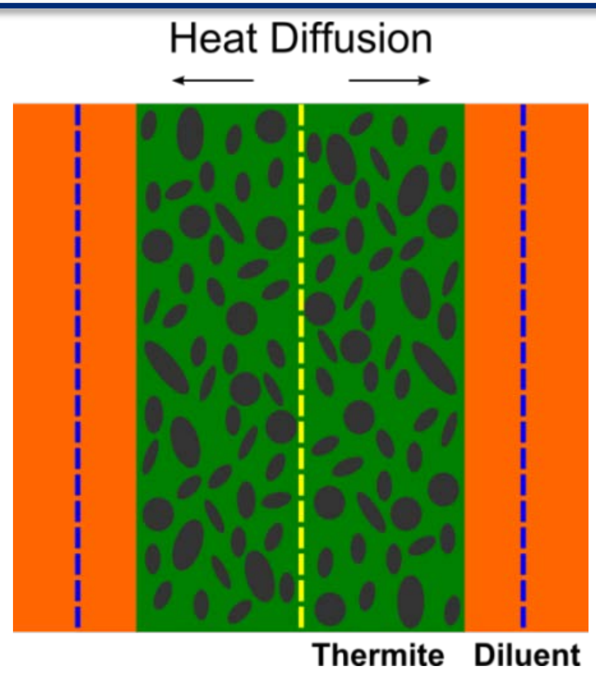
Previous Work – BM Porous Joints

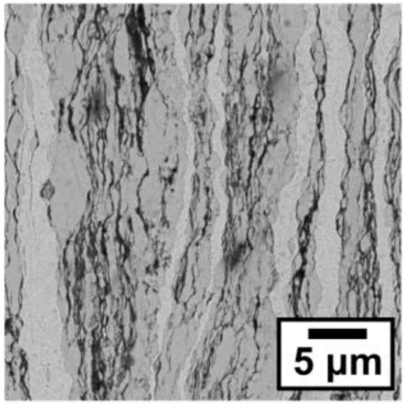


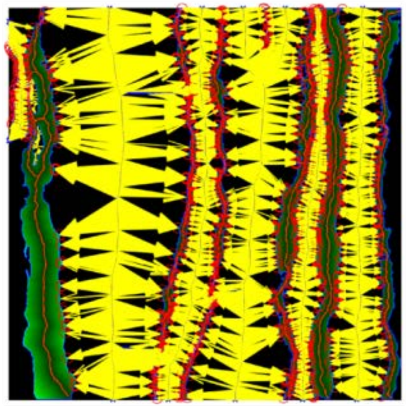


- Al:Cu_2O:20Cu BM Foil joining Al 3003 and HSBS
- Porosity due to material ejection caused by metal vapor production
- Must suppress vapor production to produce pore free joints

FEM Heat Transfer Modeling







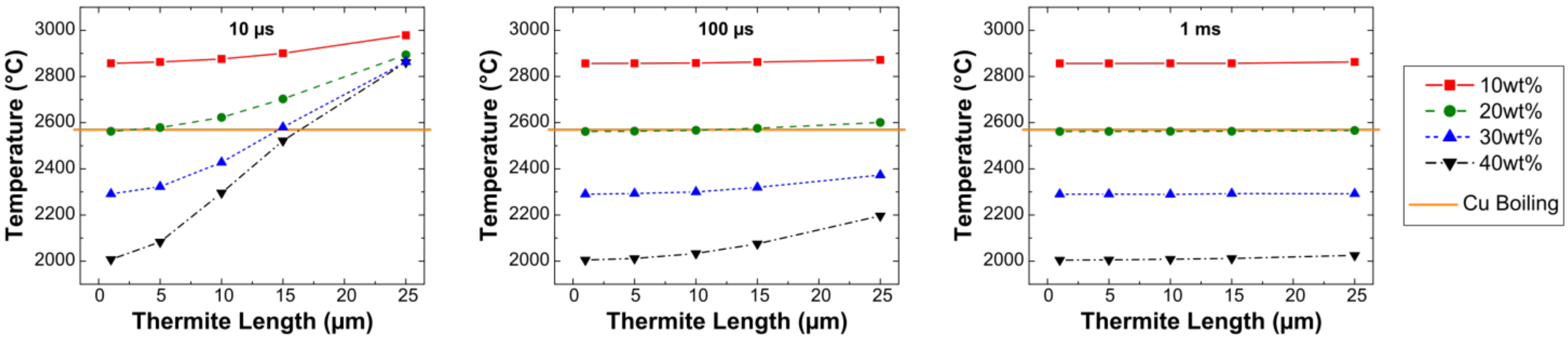
- FEM modeling of heat transfer to find critical length scales
  - **What are critical length scales for gas generation**

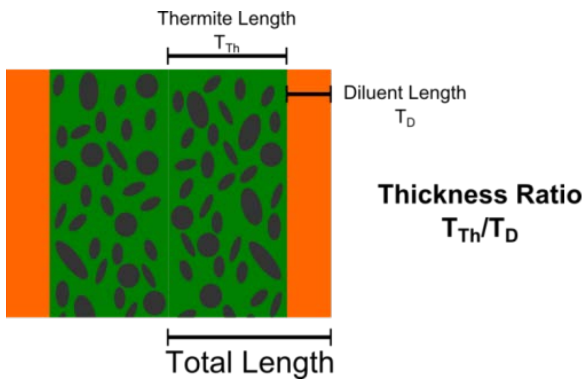
- Compare FEM with microstructural characterization
  - **What are distributions of local dilution and length scales**

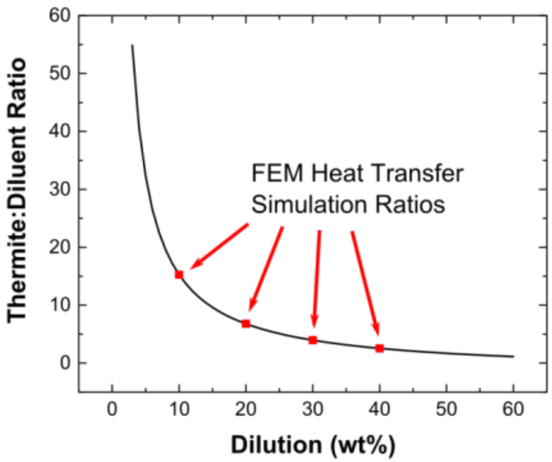
$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial x^2} + \dot{Q}_{src}$$

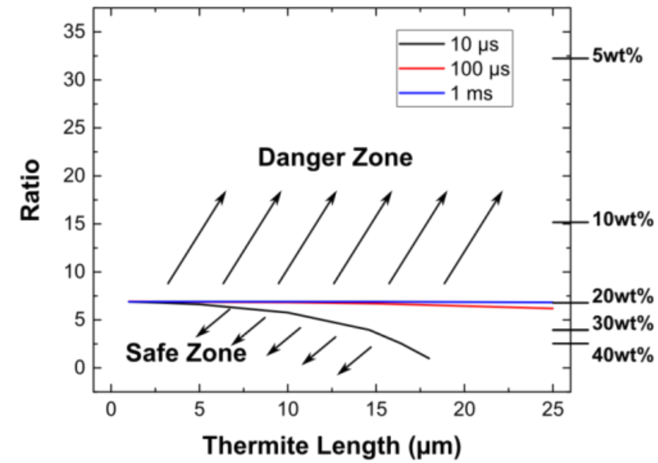
$$\alpha = \frac{k}{C_p \rho}$$

Simulation Results



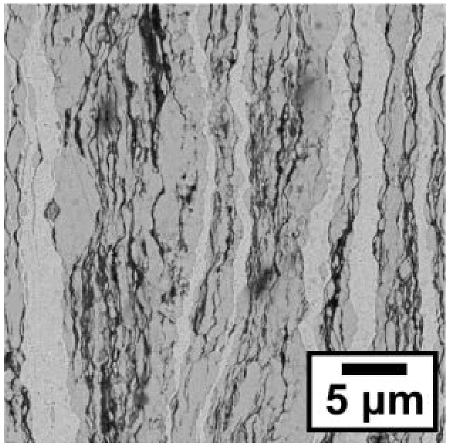


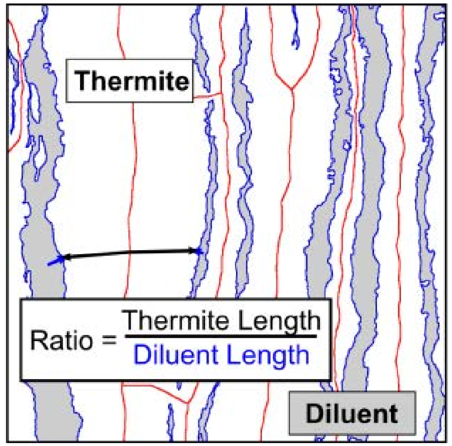


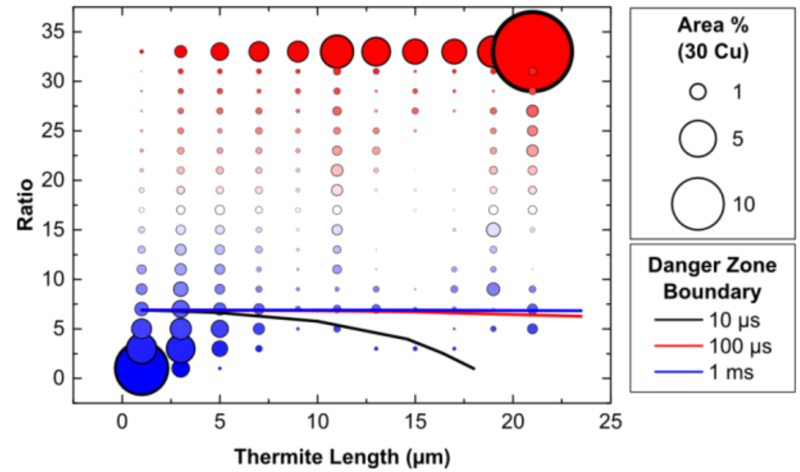


- FEM explains what thermite length scales and dilution limits allow for Cu gas production

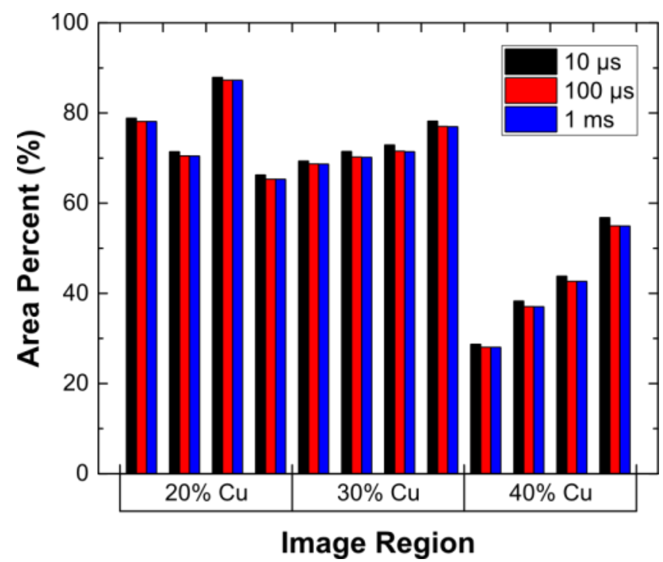
BM Microstructural Characterization



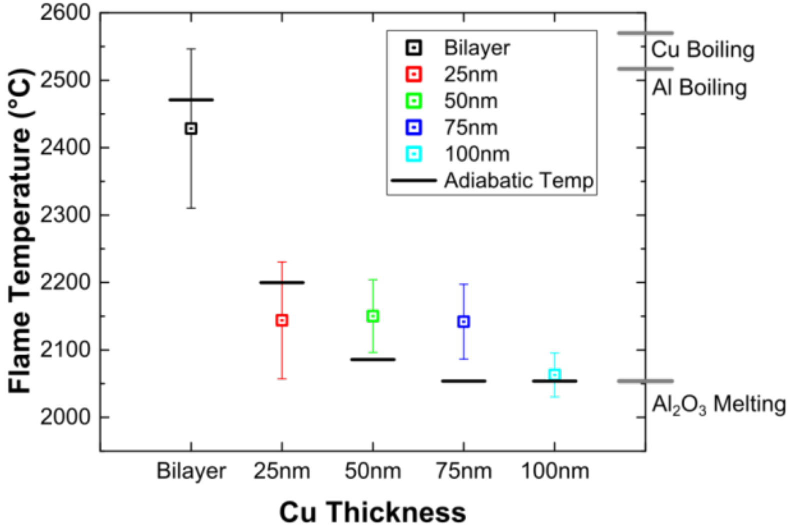


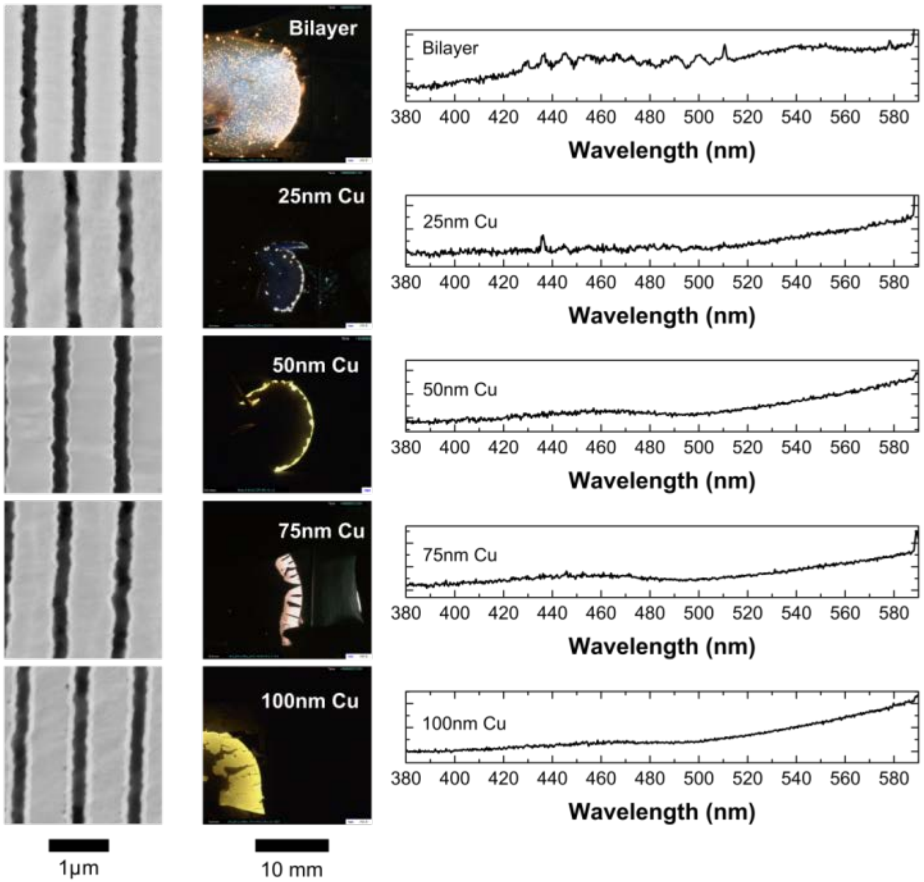


- Detailed microstructure Analysis
- Analysis demonstrates that over 50% of length scales can produce Cu vapor.
- Need to alter fabrication process to reduce detrimental length scales



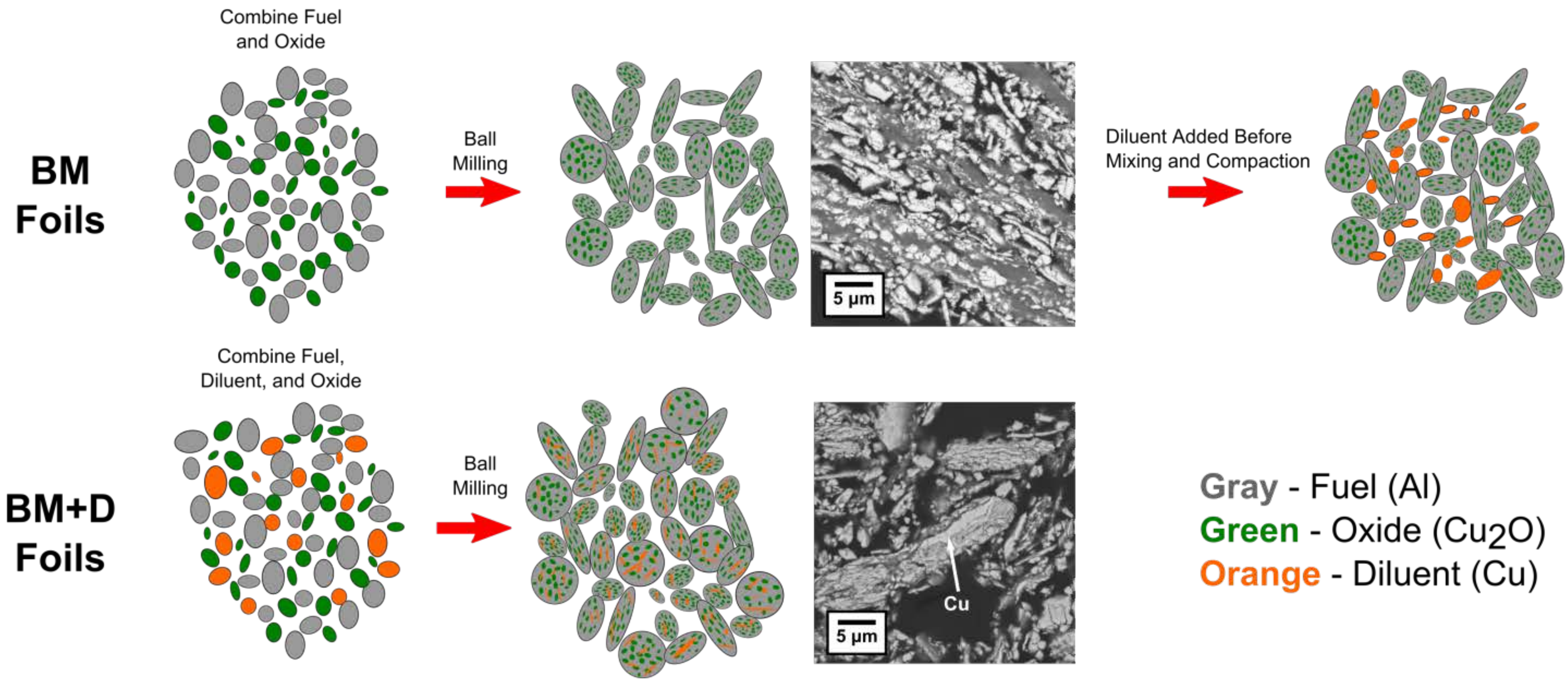
PVD Foils – Ideal Microstructure





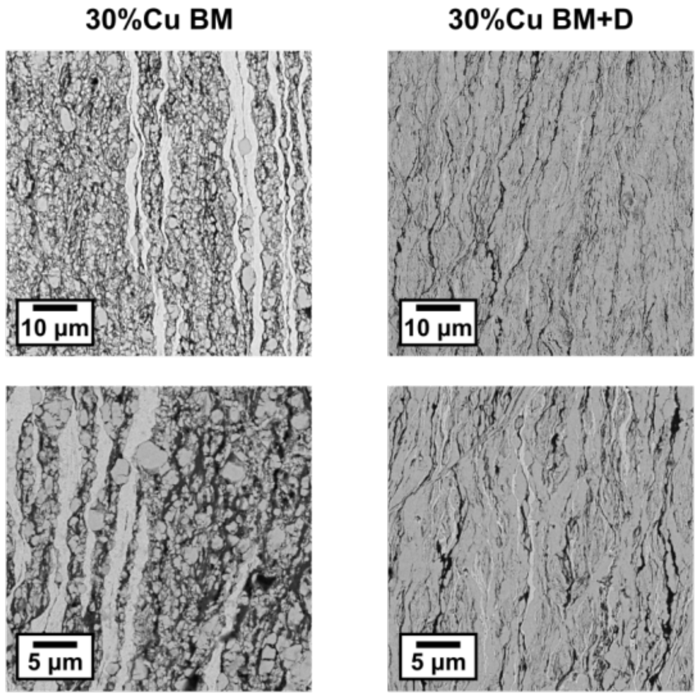
- Adding Cu interlayers decreases reaction temperature
- Suppresses vapor production

Adjusted Processing

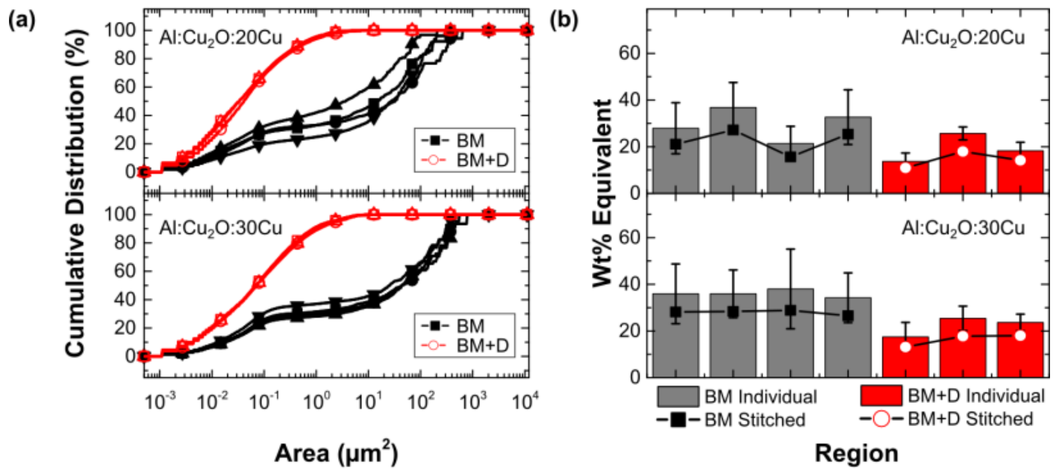


- Milling produces sub micron reactant spacing.
- Milling with diluent (BM+D) makes distribution of diluent more homogeneous.

Microstructural Comparisons

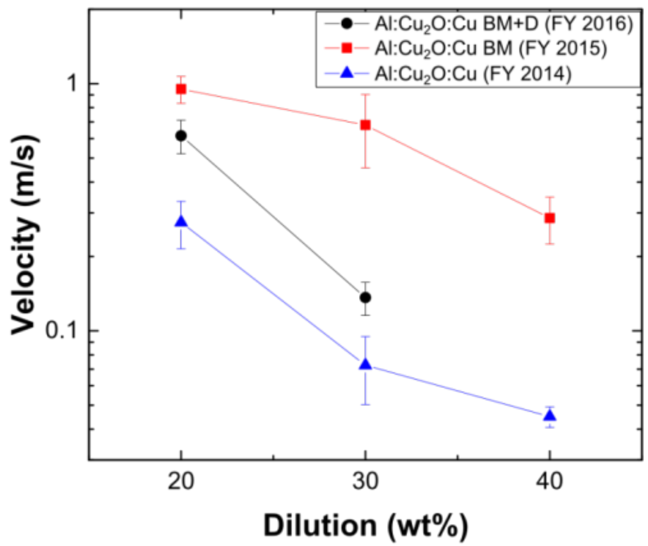


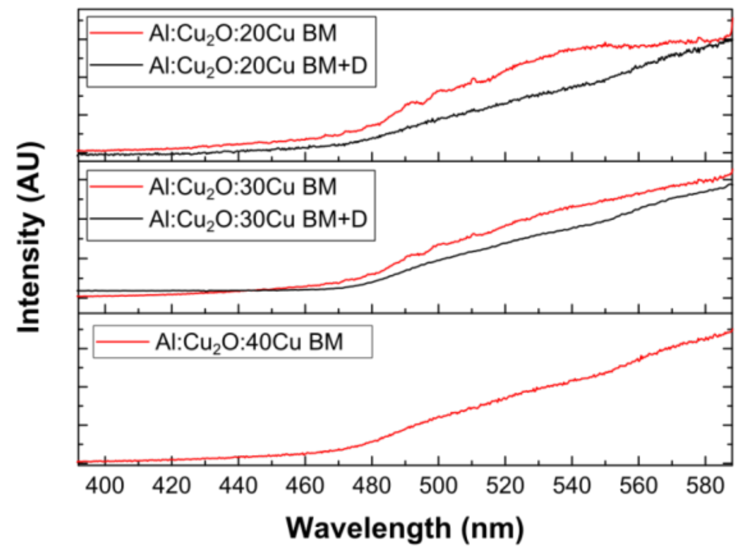
Distribution of Cu Diluent



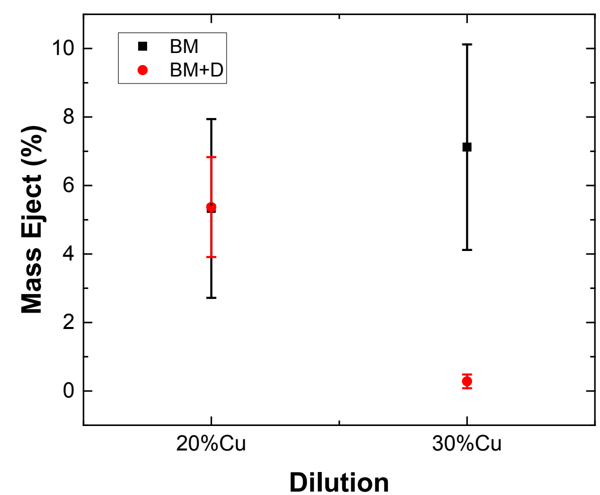
- BM+D fabrication process produces homogeneous distribution of Cu throughout microstructure
- Finer Cu particle size
- Shorter heat dissipation distances

BM+D Gas Suppression

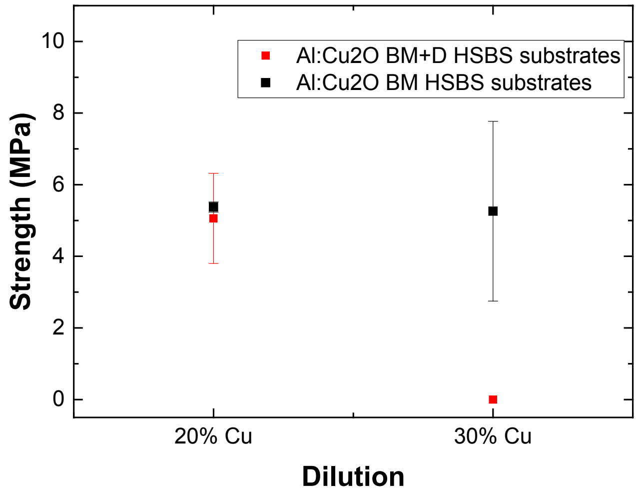


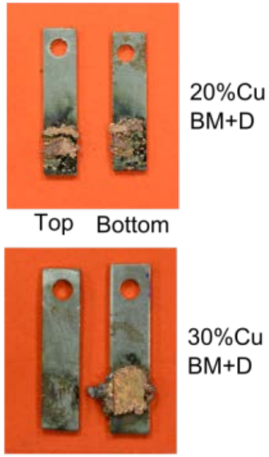


- BM+D foils do not produce any gaseous Cu vapor
- Foils remain intact during propagation
- Propagation velocity for BM+D lower than BM foils
  - Rate of heat production is lower

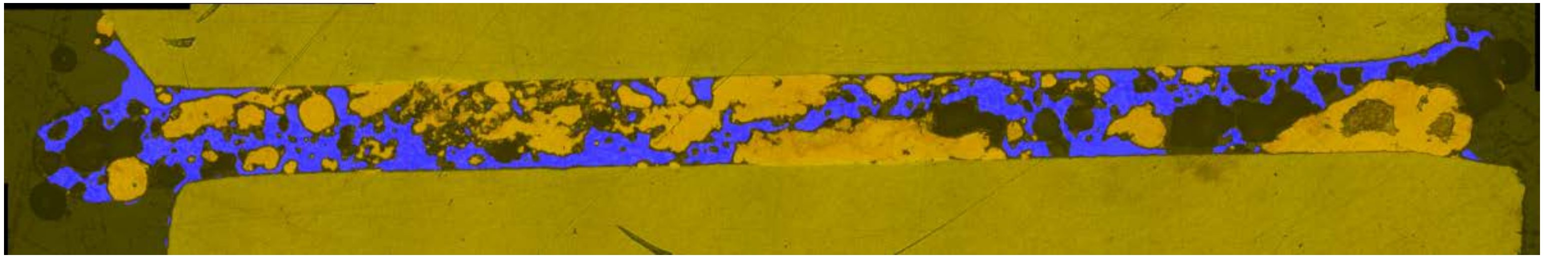


Bond Strength BM+D foils



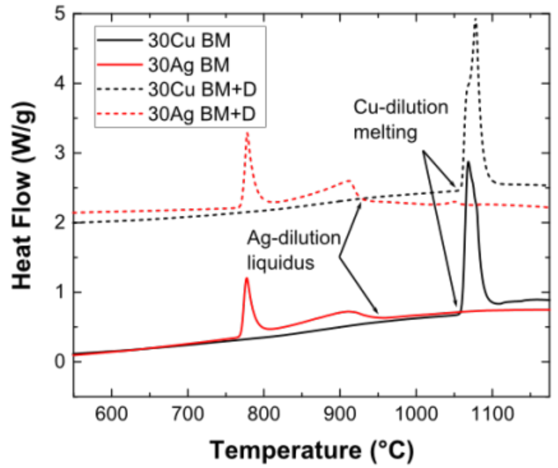


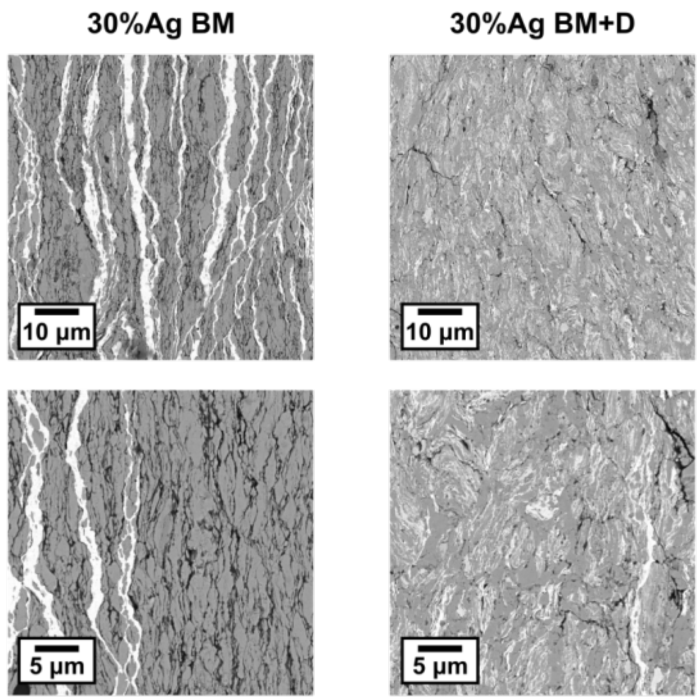
20Cu BM+D on Al 3003

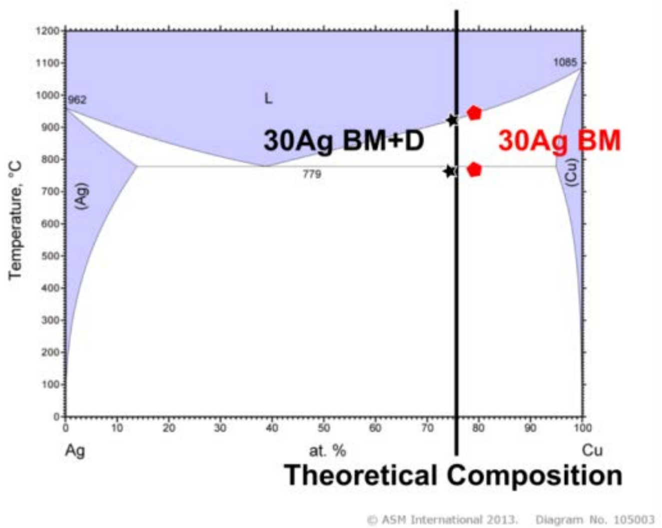


- Bond strength decreases with 30wt% dilution
- Fracture location shifts from within braze to bond interface
- Foil is not staying molten long enough to enable bonding
    - Must decrease solidification temperature of braze

Using Silver Dilution to Lower T_{melt}



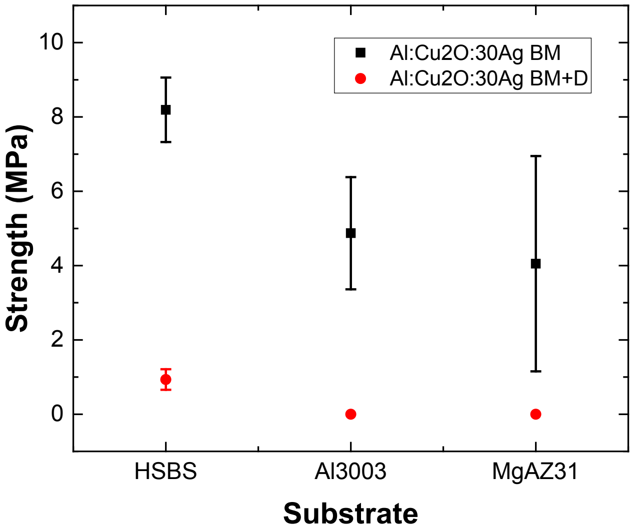




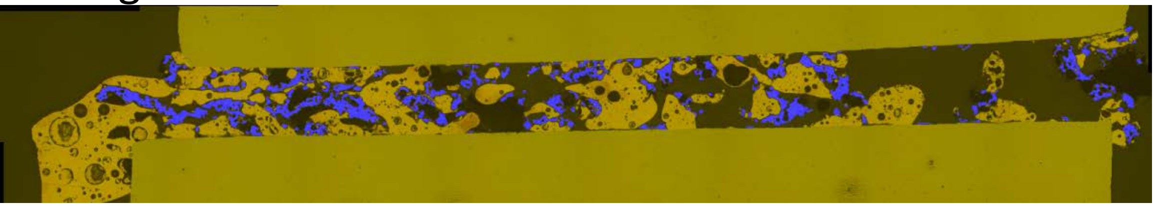
- Diluting with Ag lowers solidification temperature
- Produced BM and BM+D materials
  - BM+D propagates without gas generation

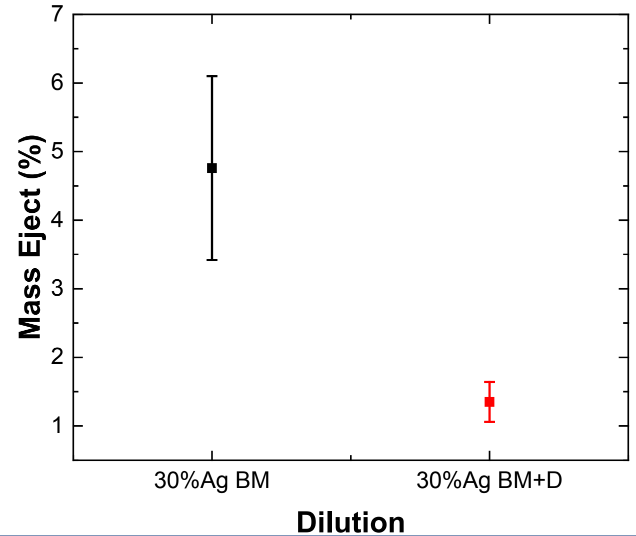
Strength of Silver Dilutions

- Diluting with Ag allows higher dilution than Cu with equivalent strength
- 30Ag BM+D ejects less mass than other foils
  - Produces lower porosity
  - Strength is limited due to heat losses



30Ag BM on HSBS





30Ag BM+D on Al 3003

Ti:B Pellets

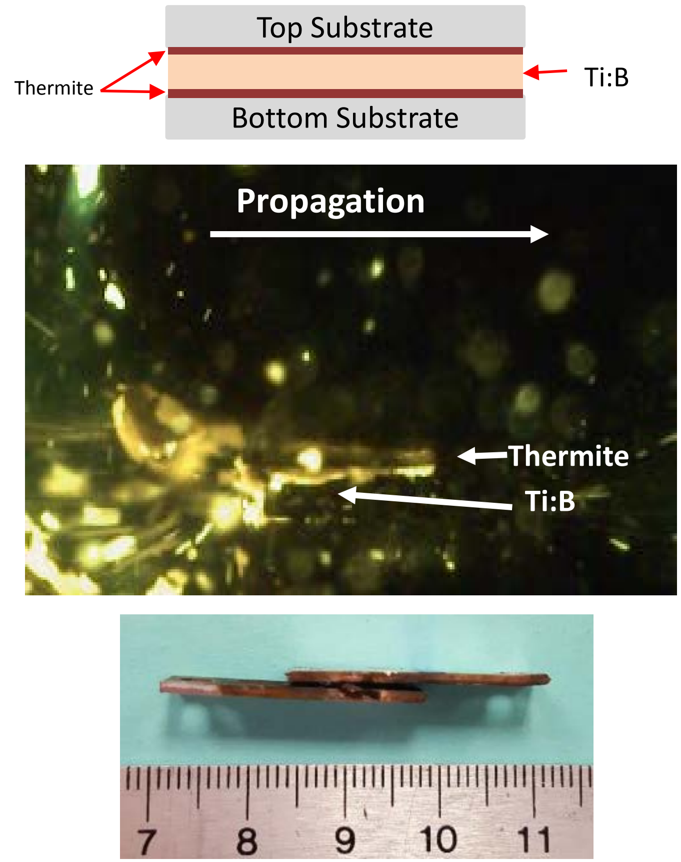
- Incorporated Ti:B BM powder into pressed trilayer pellets with BM+D thermite powders. Similar to work of Japanese group.
  - T. Matsuda, M. Takahashi, T. Sano, A. Hirose, Multiple self-exothermic reactions for room-temperature aluminum bonding via instantaneous melting, Mater. Des. 121 (2017) 136–142. doi:10.1016/j.matdes.2017.02.045.

$$2Al + 3CuO + xAg \rightarrow Al_2O_3 + 3Cu + xAg + Heat$$

$$Ti + 2B \rightarrow TiB_2 + Heat$$

- Synthesized TiB_2 serves as hot, porous, mechanically strong scaffold
- Molten braze metal flows into porous TiB_2 matrix
- Additional pore filling from molten Al 3003 substrate

(a)
(b)
(c)



(a) Schematic representation of bonding with a trilayer pellet and (b) video of such a pellet propagating between two Al 3003 substrates producing the joint shown in (c).

Response to Previous Year Comments

- *The reviewer commented that the presenter only listed two sources for collaboration and coordination; one is a fellow researcher and post-doctoral employee, and the second is a supplier of material to be tested. There is no collaboration with potential sources in the supply chain or with manufacturers who would be interested in the technology, if the research is successful. The reviewer observed minimal collaboration and no OEMs.*
  - We have increased our collaborative activities this year. In addition to working with more members of the JHU community, we have worked with TARDEC and 3M to bring this technology to market.

- *The reviewer said it potentially supports DOE goals, but is essential to identify a potential target customer soon to ensure that there will be a return on the investment.*
  - The technology is still in the early stage to find a target costumer, but we are actively collaborating to ensure technology transfer.

- *The reviewer said that although the objective stated that the effort is to develop and characterize novel reactive foils for use in bonding dissimilar materials, there is nothing in the written or oral presentation that explains how this research will be used in lightweighting applications that will directly support the overall DOE objectives to make lightweight vehicles that will displace or reduce the use of petroleum. The relevance discussed applies to determining the best chemistry and increasing quantity of braze in the foils from 65% to 74%, which is relevant to research goals, not DOE goals.*
  - We highlight that this technology addresses the gap in current abilities to join dissimilar metal combinations and provides and new cost effective technique to do so.

Collaborations

- **Severstal** – Material supplier
- **Dr. Karsten Woll** – Former postdoc
  - Now at Karlsruhe Institute of Technology
- **Dr. James K. Guest and Dr. Reza Behrou** – Heat Transfer Modeling
  - Johns Hopkins University
- **TARDEC** – Tank body ceramic bonding

Remaining Challenges and Barriers

Challenge: Foil not hot enough to allow braze to flow

Solution: Use hot Ti-B scaffold to keep braze molten and enhance wetting

Challenge: Organic contamination on powders produces some vapor leading to porosity

Solution: Heat treat powders before and after processing to remove contamination

Challenge: Best braze(s) may lead to corrosion

Solution: Alloy braze systems to minimize corrosion

Future Work

- Incorporate Ti-B trilayer into bonding process to enhance wetting of molten braze

- Continue optimizing bonding parameters for given Redox Foil/base metal couples, including optimization of surface preparation, bonding pressure, and foil thickness.

- Create statistically signification datasets for shear strengths of bonds and determine the modes of failure in the joint.

- Analyze the braze and base metal interface for any changes in mechanical properties of base metal due to heating from the reaction of the Redox Foil.

Any proposed future work is subject to change based on funding levels.

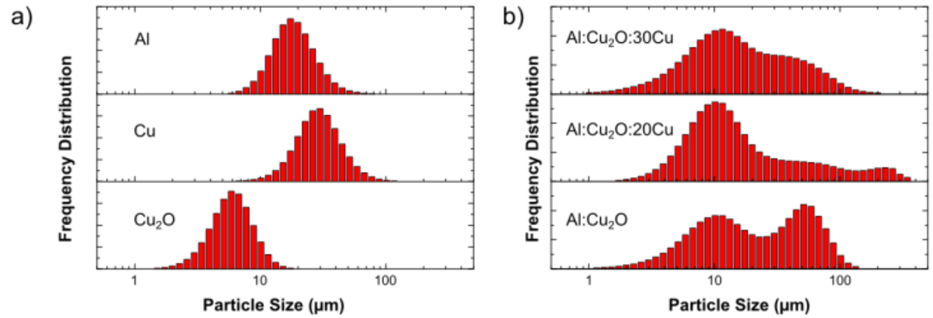
Summary

- Determined Cu vapor as gas species in BM Foils.
- Characterized critical length scales and dilutions necessary to suppress vapor production.
- PVD foils demonstrate ability to avoid gas production given controlled microstructure.
- BM+D foils able to suppress Cu vapor production.
- Ag dilution able to lower solidification temperature of braze.

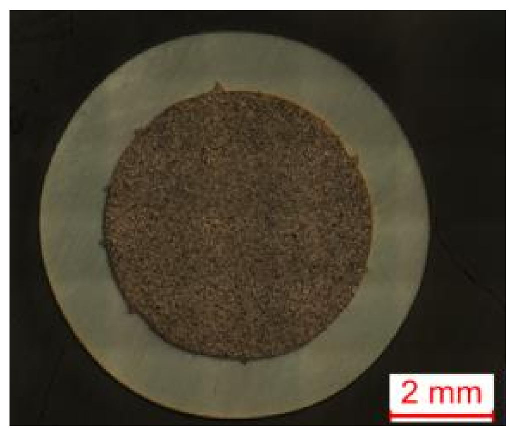
Technical Back-Up Slides

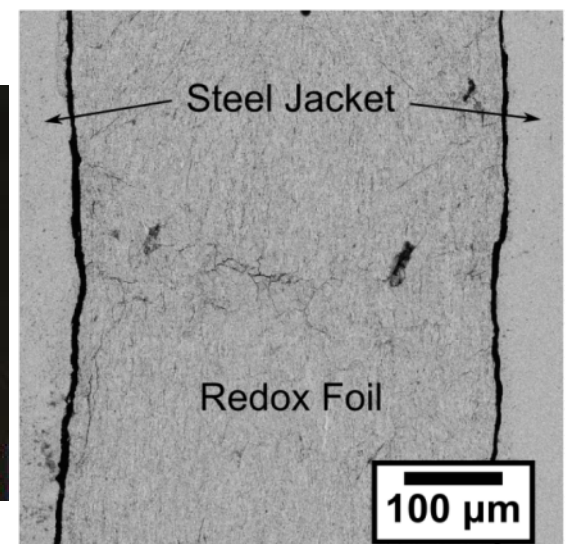
Mechanical Fabrication of Redox Foils

- Pack powders in tube
  - $Al:Cu_2O:Cu$
  - Starting powders on order of 10-20 µm
  - Milling increases powder size but decreases spacing

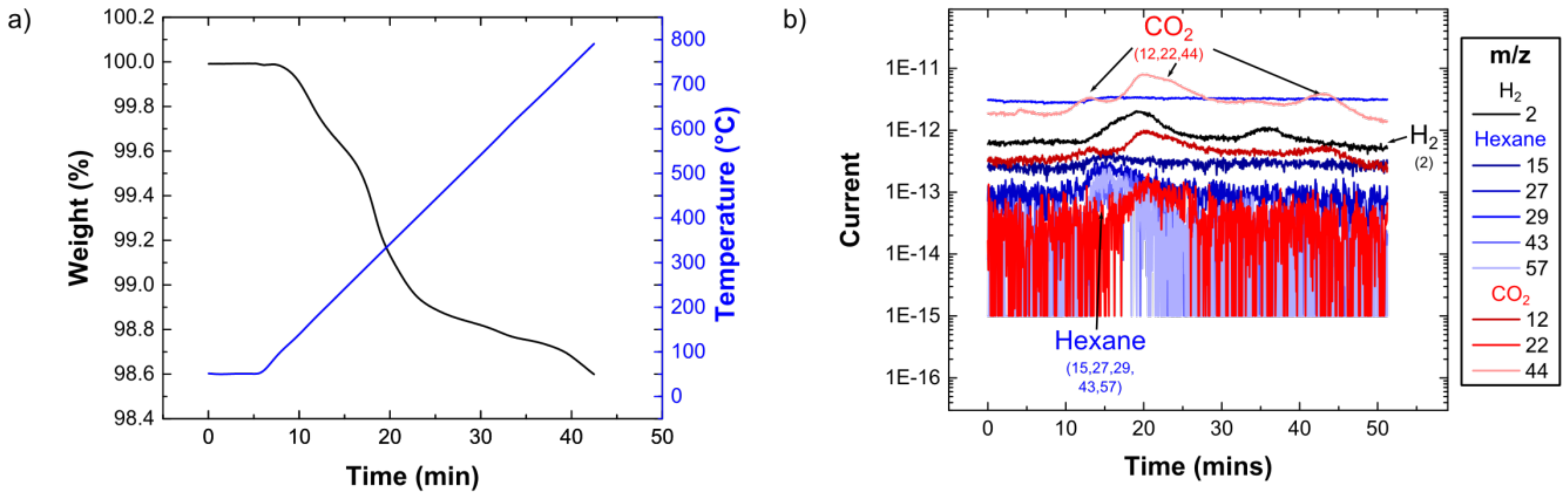


- Process
  - Swage: radial reduction 0.59" to 0.22"
  - Roll to desired thickness
  - Remove steel jacket





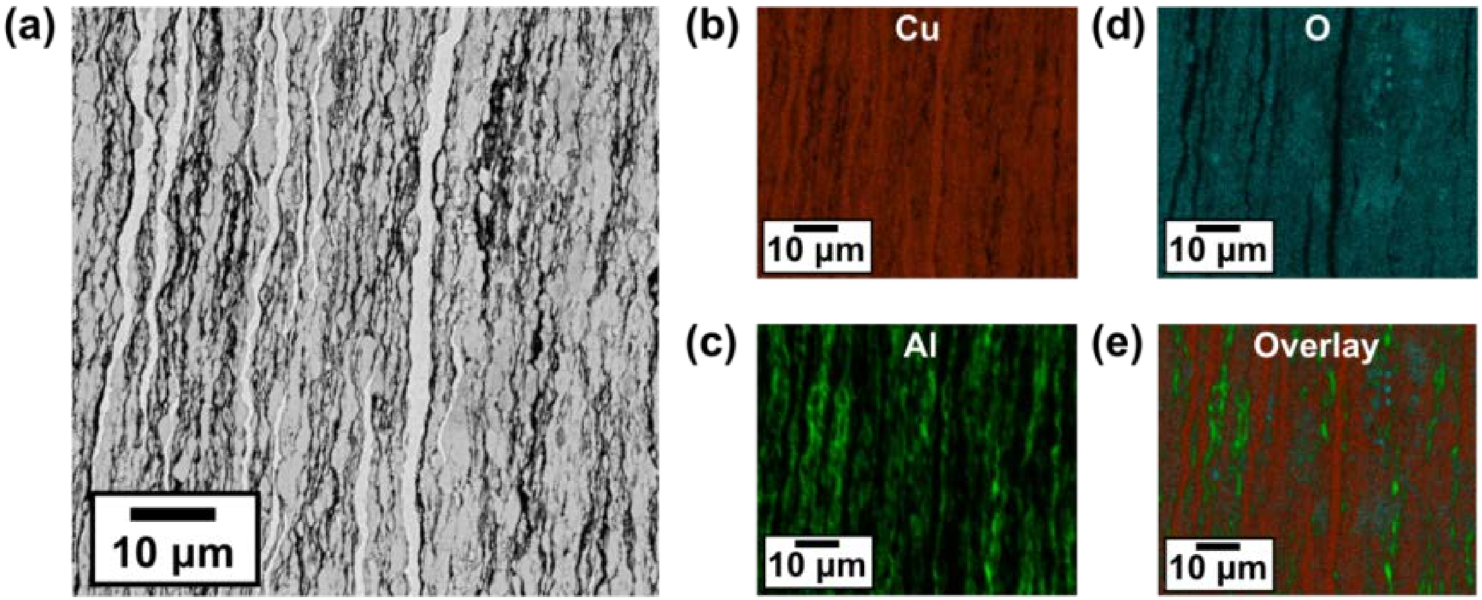
Mass Loss Al:Cu_2O BM Powder



- First mass loss event is due to hexane
  - Comes from the milling process

- Second and third events are H_2 and CO_2
  - Organic contamination on starting powders

Composition Confirmation



a) SEM used for EDS

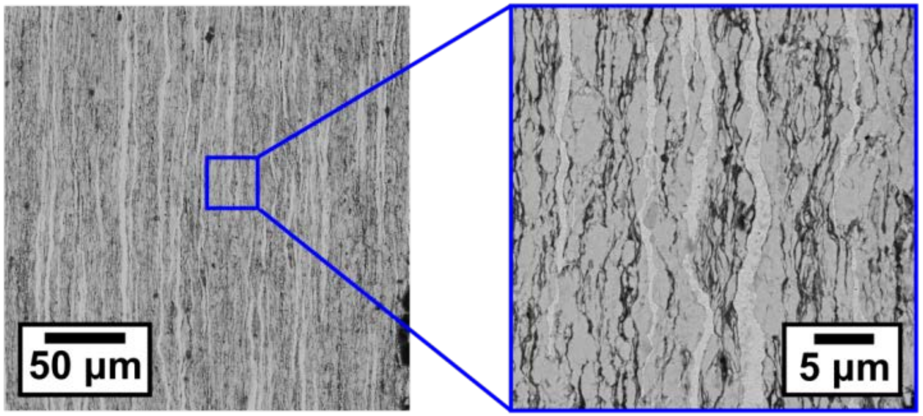
b) Cu scan – lightest SEM corresponds to pure Cu

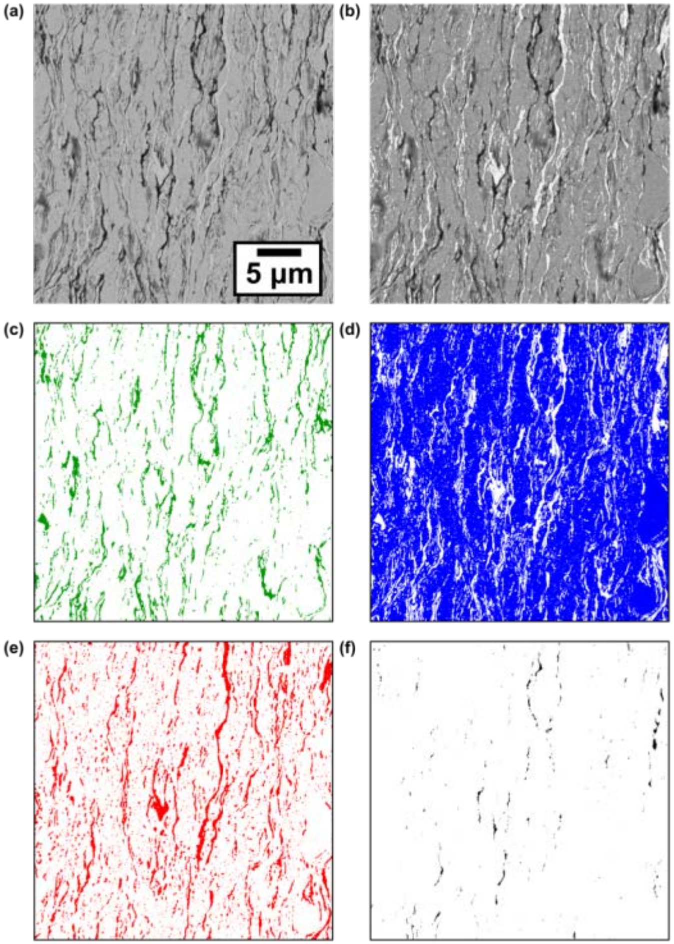
c) O scan – used to confirm location of Cu_2O

d) Al scan – confirms dark pixels are fuel

e) Overlay – confirms species

Image Analysis





- Image analysis performed on stitched images
  - 64 images acquired at 8kx magnification (33.789 nm/pixel)
  - Field of view ~250µm
- Thresholding algorithms used to determine phases

Image Analysis